

<b>Project</b>	AtlantOS – 633211
<b>Deliverable number</b>	8.1
<b>Deliverable title</b>	Storm surge climatology report
<b>Description</b>	Any increase in flood frequency or severity due to sea level rise or changes in storminess would adversely impact society. It is crucial to understand the physical drivers of extreme storm surges to have confidence in the datasets used for extreme sea level statistics. We will refine and improve methods to the estimation of extreme sea levels around Europe and more widely. We will do so by developing a comprehensive world picture of storm surge distribution (including extremes) for both tropical and extra-tropical cyclones. We will apply statistical methods to both tide gauge data and multi-decadal runs of numerical models. We will advance the development of a consistent global storm surge climatology, building on the work of the IOC/WMO JCOMM Expert Team for Waves and Coastal Hazards [D8.1] [NOC]
<b>Work Package number</b>	8
<b>Work Package title</b>	<b>Societal benefits from observing/information systems</b>
<b>Lead beneficiary</b>	NOC
<b>Lead authors</b>	Kevin Horsburgh, NOC
<b>Contributors</b>	Joanne Williams, NOC; Caroline Cussack, MI
<b>Submission date</b>	6 April 2017
<b>Due date</b>	31 March 2017
<b>Comments</b>	This deliverable was slightly delayed to ensure we could report positive progress on the new version of the unstructured global tide-surge model (based on an improved representation of the ice sheet grounding line in the southern ocean)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 633211.



## **Storm surge climatology report**

### **1. Background**

Coastal flooding represents one of the major challenges of global climate change for humanity. It is estimated that by 2070, approximately 150 million people and \$35,000 billion of assets will be exposed to a 1 in 100 year flood event. Any increase in flood frequency or severity due to sea level rise or changes in storminess would adversely impact society. Storm surges and oceanic waves are the major cause of extreme sea levels and devastating coastal impacts along many coastlines around the world. Impacts of storm surges are realised through significant human tolls and economic impacts. Recent examples include the storm surge resulting from Typhoon Nargis in Myanmar in 2008, which killed 138,000 people (IPCC, 2012) and Hurricane Sandy in 2012 for which the US death toll was 106 people and damage estimates exceeded \$60 Billion.

Despite the significant potential impacts of these events, recent scientific assessments of future projections of storm surges and waves have low confidence due to (1) the relatively small number of assessments, (2) the different methods and models used to investigate future changes and (3) the limited regional coverage of these assessments (see for example IPCC, 2012; Church et al., 2013). In order to improve our ability to assess the potential change of storm surge it is critical to have a well established baseline of storm surge climate, based on consistent techniques. This demands a coherent approach to deriving the statistics of past storm surge occurrence as well as an agreed set of models and tools that can then be applied to future climate change projections, once climate models are reproducing weather at a resolution that renders them suitable for analysis of storm surges. The ocean wind-wave climate community has started to address these challenges for ocean wind waves through the collaborative project COWCLIP (Coordinated Ocean Wave Climate Project, Hemer et al., 2013) – an international project to coordinate regional scale wave model simulations and to investigate the role of climate change on future wave climate. This Task in AtlantOS is laying the framework for a complementary international effort around storm surges. Developing a global storm surge climate has been adopted as a project under the IOC/WMO JCOMM Expert Team for Waves and Coastal Hazards. This Task is an early contribution to that international coordination which will be announced in a keynote presentation at the forthcoming WCRP Regional Sea Level conference in New York, in July 2017. See:

<https://www.wcrp-climate.org/news/wcrp-news/991-international-wcrp-ioc-conference-regional-sea-level-changes-and-coastal-impacts-13-09-2016>

### **2. Storm surges and climate change**

Storm surges are the large scale increase in sea level due to a storm. The same physics controls storm surges caused by mid-latitude weather systems (extra-tropical cyclones) and tropical cyclones, hurricanes and typhoons. They are caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure (Pugh and Woodworth, 2014), although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and coastal topography. Storm surges driven by mid-latitude weather systems can increase sea levels by 3-4 m and tropical cyclone surges can be as high as 10 m. These devastating increases in sea level last from hours to days and span hundreds of square kilometres.

There is currently low confidence in future climate storm surge projections because of the lack of consistency between climate models, and limitations in the model capability to simulate extreme winds (IPCC, 2012). IPCC (2013) confirms that at most locations mean sea level is the dominant driver of observed changes to sea level extremes although large-scale modes of variability such as the North Atlantic Oscillation (NAO) may also be important. There is evidence of increases in extreme water levels over the past 100-200 years around many parts of the global coastline, including around the UK (e.g. Menendez and Woodworth, 2010). While changes in storminess could contribute to changes in sea level extremes, there is little or no evidence for either systematic long-term changes in storminess or any detectable change in storm surges (IPCC, 2012). The scientific consensus is that any changes in extreme sea levels at most locations worldwide have been driven by the observed rise in mean sea level (e.g. Woodworth and Blackman, 2004; Menendez and Woodworth, 2010; Marcos et al., 2015; Wahl and Chambers 2016).

The coastal impact of storm surges will continue to increase under rising sea levels, while possible future changes in global atmospheric circulation and weather patterns may further influence likelihoods of severe storm surges (and waves) through changes in the frequency and severity of severe weather. A consistent baseline of storm surge occurrence at the regional scale is essential for robust coastal planning and adaptation, and to identify any future temporal or spatial changes to storm surges should they occur.

### **3. Aims of this work**

One of the reasons why there has not yet been any global storm surge intercomparison equivalent to COWCLIP (Hemer et al., 2013) is that storm surges are episodic and localised phenomena. Unlike ocean surface waves, there is no unified global programme of storm surge observations: they are not amenable to ship measurements because a coastline is necessary to act as a waveguide for storm surge formation, and instantaneous satellite measurements from altimetry are not sufficiently accurate. Within Task 8.2 we have undertaken to provide a systematic approach to isolating storm surge from a tide gauge record and to improve the application of joint probability methods to estimate extreme sea levels around Europe (in the first instance) and ultimately more widely. Additionally, in the remainder of the project we plan to work with collaborators (Deltares, Netherlands) to establish a validated global numerical model for both storm surges and tides. We will apply improved statistical methods to both tide gauge data and multi-decadal runs of numerical models. This will lead to a final product of a global picture of storm surge climate from a single model validated for both global tides and regional storm surges. The results will advance our scientific knowledge of storm surges as well as provide policy guidance to decision makers and planners.

### **4. Advances in storm surge analysis derived from tide gauge records**

In regions with significant tidal range, storm surges represent the greatest threat when they coincide with tidal high water. Furthermore, it is important to understand the exact interactions between storm surges and tides. Williams et al. (2016) have published new understanding about how storm surges and high tides interact, providing the first systematic proof that any storm surge can occur on any tide as shown in Figure 1 – which advances statistics for extreme water levels [this paper is an output of AtlantOS]. Showing that the magnitude of high water exerts no influence on the size of the most extreme skew surges provides a sound statistical basis for applying joint probability statistics which

allow any storm surge to occur on any tide. The lack of observed storm surge dependency on water depth emphasizes the dominant natural variability of weather systems.

This is important and timely for scientific and engineering reasons: policy makers and coastal protection agencies are currently revising extreme sea level projections following the fifth assessment report of the IPCC. Understanding the relationship between skew surge and tide will ensure that correct impacts conclusions are drawn. Our work will improve the extreme value analysis for storm which will form future work under Task 8.2.

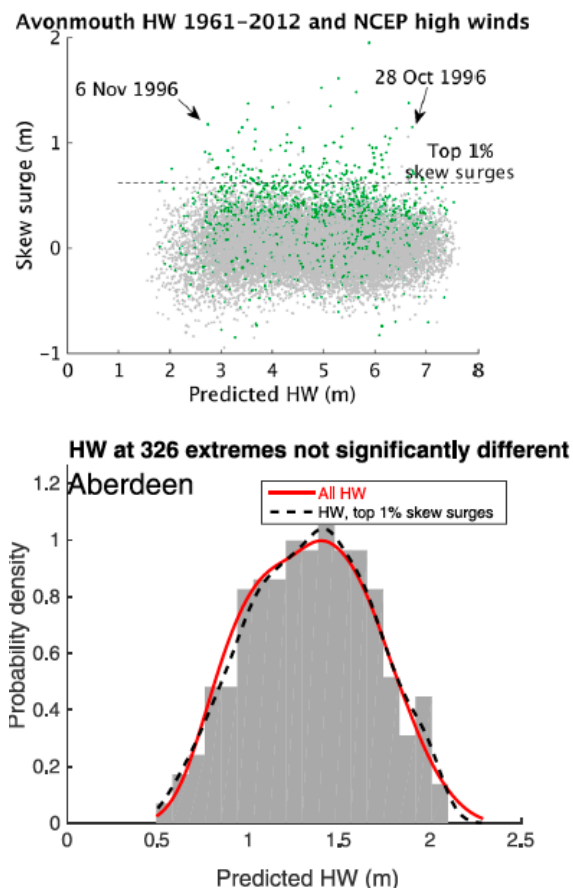


Figure 1. Independence of skew surges and tides from an observational record (example is from Avonmouth tide gauge in the UK). Top panel shows no correlation between skew surge and coincident tide (green dots are the top 1% of skew surges). Lower record shows that tidal distribution from selected extreme surges and distribution from all high waters in the record are not significantly different. For full details see Williams et al. (2016)

This work also confirms the most useful measure of storm surge is the skew surge - which is the difference between the maximum observed sea level and the maximum predicted tidal level, regardless of their timing during the tidal cycle (e.g. de Vries et al., 1995). Hence each tidal cycle has one predicted high water value and one associated skew surge value. The advantage of using the skew surge is that it is a simple and unambiguous measure of the storm surge and that the effect of the meteorological forcing is integrated over a tidal cycle.

Williams et al. (2016) analysed tide gauge data from extratropical gauges in the North

Atlantic, from the UK, Ireland, Netherlands and US East coast. We now intend to extend this result globally, using the GESLA2 data set (see Figure 2), which collates high-frequency tide gauge data from around the world (<http://www.gesla.org/>)

**GESLA**  
Global Extreme Sea Level Analysis  
Version 2



*Figure 2. GESLA extreme sea level stations*

We will go on to investigate whether the same independence persists in all tidal and weather regimes. Our previous analysis was restricted to high-quality records in extratropical regions. This extension of the work may provide insight into the comparative behavior of tropical surges, although there remains a likely problem of insufficient data. It seems likely that the surge response of more intense wind stresses and pressure gradients associated with tropical cyclones would make any tidal effects second order, but we may need to confirm that using numerical models. The GESLA data includes many gauges which are difficult to analyse. Initially, we have applied some broad criteria to exclude data: if the record is shorter than 20 years, if there is a gap of longer than 3 years, or if any monthly median is more than 4 standard deviations away from the skew record (to avoid datum shifts). This eliminates around two-thirds of the data, but there remain 475 time series around the world. Unfortunately these selection criteria leave long gaps on the west coast of Africa, Indian Ocean, the Arctic and Antarctica.

We show our preliminary results here but stress that further detailed analysis and data screening is ongoing to apply robust selection criteria. These interim results are shown in Figure 3 below where the same techniques as in Williams et al. (2016) have been used, applying a seasonal correction to allow for known relationships between tide and severe weather. After further development, this global investigation into skew surge distributions and behavior will deliver another peer-reviewed publication for AtlantOS. Our provisional analysis shows that of the 475 records used, 73 show an increased likelihood of extreme surge on neap tide, and 8 show an increased likelihood on spring tide. 394 show no statistically significant relationship. In Figure 3, the circle is scaled with the tidal range, and the yellow crosses mark gauges we have excluded. Pink circles indicate an increased likelihood of extremes on neap tides, blue circles increased likelihood on spring tides. More detailed investigation of these results is required before we can draw firm



conclusions. For example, some of the gauges contain known datum shifts, and others exhibit long-period sea-level variability with other known cause, such as relationships with ENSO.

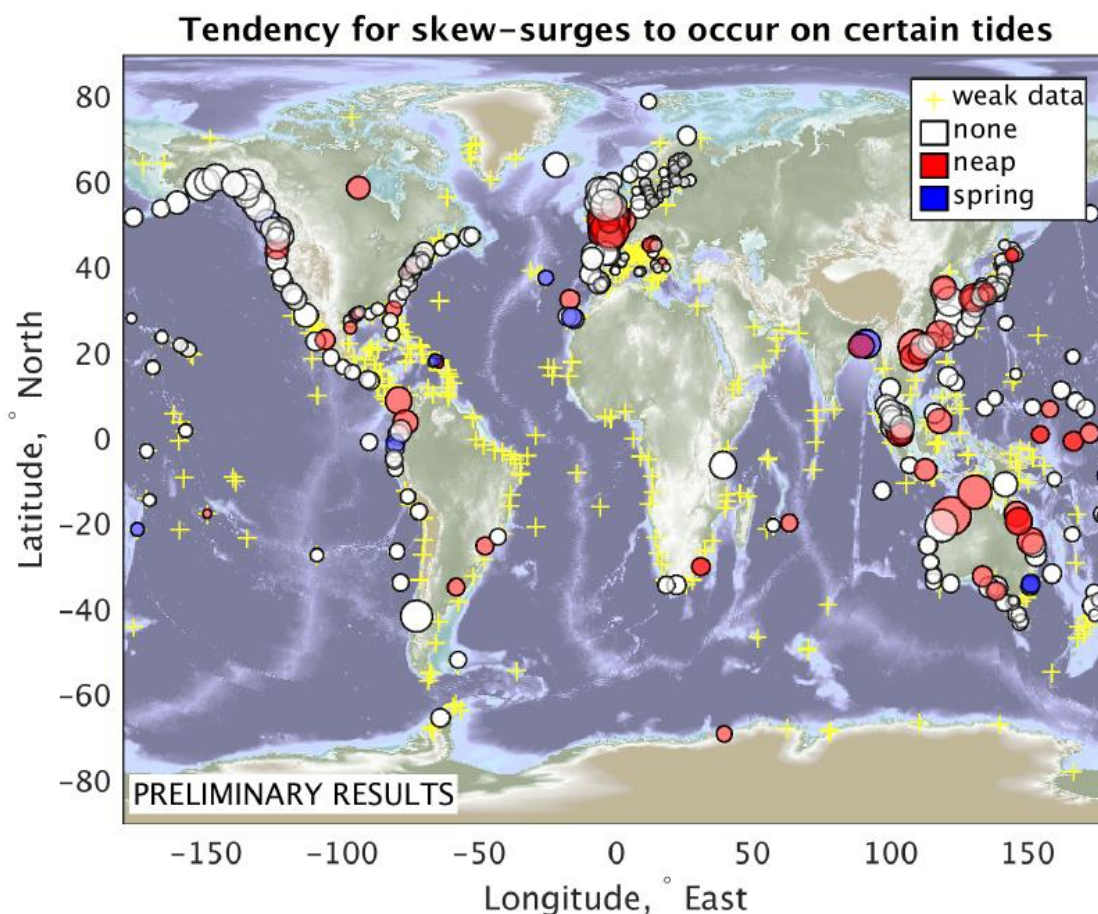


Figure 3. Preliminary results of the global extension of Williams et al. (2016) using the GESLA data set

## 5. Modelling storm surge climate

Defining storm surge climatology as the study of storm surge climate (i.e. the statistics of storm surge behavior) then one quickly concludes that despite the huge literature on storm surge modelling (over 200 peer-reviewed papers have been published on the topic 2014-2016) little of it lends itself to the development of a unified global storm surge climate. Many of the model studies in the examples that follow are designed either as hindcast simulations of specific storms and storm surges that caused damage, or are regional simulations with inconsistent model physics and inconsistent meteorological forcing.

For extra-tropical storm surges there have been many European reanalysis studies (using ERA40, ERA interim or NCEP reanalyses) to provide baseline values against which to then infer changes from regional climate model forcing (e.g. Lowe et al., 2009; Sterl et al., 2009). These numerous studies have used regional climate model forcing to drive storm surge and wave models to infer changes in extreme sea level for the Mediterranean (Conte and Lionello, 2013; Jordà et al., 2012), North Sea (Debernard and Røed, 2008;

Howard et al., 2010), as well as the Atlantic coast of Europe (Lowe et al., 2009; Marcos et al., 2012) and Baltic Sea (Gräwe and Burchard, 2012; Meier et al., 2004), with a recent pan-European study by Vousdoukas et al. (2016). Although some of these studies suggested increasing levels of storm surge along parts of northern Europe, most conclude that the statistical significance of changes in storms, or severe storm surges, is negligible for European coastlines. Haigh et al. (2016) also use NCEP reanalysis fields to drive a European shelf storm surge model and then analyse the spatial footprint and temporal clustering of extreme sea level and skew surge events around the UK coast over the last 100 years (1915–2014).

Neither reanalysis atmospheric forcing nor regional climate models are especially suitable for modelling storm surges caused by tropical cyclones. These types of atmospheric model lack the resolution to properly represent the intense low pressures or strong wind fields in tropical cyclones. Nevertheless, various climate modelling studies have attempted to draw conclusions about future changes in storm surge properties based on regional climate forcing: examples include Balaguru et al. (2016) for Florida and the Gulf of Mexico; McInnes et al. (2014) for the South Pacific; Mori and Takahmi (2016) and Yasuda et al. (2014) for east Asia; Cannaby et al. (2016) for Singapore. Zhang and Sheng (2015) force a two-dimensional storm surge with an enhanced reanalysis by inserting a parametric vortex into the reanalysis fields to better represent atmospheric forcing for a tropical storm. The tidal and surge-induced sea levels were then used to estimate the 50-year extreme sea levels associated with tides and storm surges over the northwest Pacific.

The simulation of individual storm surges is normally designed to investigate, in detail, the ability of particular local and regional models to accurately model storm surges which caused significant damage and loss. Examples of these types of storm-specific hindcasts include Hurricane Katrina (e.g. Yang, 2016) and the Patriot's Day storm (Xie et al., 2016) in the USA. Severe storm surges in the Bay of Bengal have been re-simulated by Gayathri (2016) and Pattanayak (2016) who used a one-way coupling of the Non-hydrostatic Mesoscale Model core of Weather Research and Forecasting (NMM-WRF) system with the two-dimensional finite-difference storm surge model developed at the Indian Institute of Technology Delhi (IITD). As a result of its destructive effects in the Philippines, Typhoon Haiyan has been modelled in detail. On 8<sup>th</sup> November 2013, Typhoon Haiyan (or Typhoon Yolanda) caused catastrophic damage with the majority of the death toll (estimated at over 6,000) due to the storm surge that struck Tacloban City, Philippines. Kim et al. (2015) examined the role of sea surface drag in a coupled surge and wave model; Mori et al. (2014) studied the local amplification in Leyte Gulf; and Lee and Kim (2015) demonstrated the importance of including wave breaking in a model of coastal impacts. One clear common conclusion from focussed model studies of tropical cyclone surges is that the selected relationships between tropical cyclone parameters (in idealised cyclone models) are key to accurate simulations. For Typhoon Haiyan, Takagi and Wa (2016) found that estimating R-max using the 50-kt wind radius was more effective than the central pressure or maximum wind. Since numerical weather prediction models cannot yet represent the complex structure of tropical cyclones, idealised parametric models currently provide the best approach to storm surge simulation. The freedom of their parameters makes intercomparisons between studies difficult. Since most studies target an individual storm, sufficient data is not available to draw statistical conclusions about the distribution of storm surge magnitudes at any location.

A more effective, but not entirely physical approach, to generating storm surge vulnerability statistics is to synthesise a large number (typically many thousands) of storms using Monte Carlo style techniques. Using stochastic models for the tracks of tropical cyclones allows the generation of a suitably large number of synthetic cyclone tracks on which to base extreme value statistics. There are various approaches but a typical one is to use a Poisson sampling process to generate an appropriate number of events based on observed annual frequencies within some specified region of a model domain (e.g. a 100 km x 100 km cell). Monte-Carlo sampling of probability distributions is then used to assign each synthetic event; an initial pressure distribution, forward speed, direction and radius of maximum wind. Following its genesis, each synthetic cyclone is then propagated using autoregressive techniques to determine the values of forward speed, direction and central pressure at its next location, following Vickery et al. (2000). Haigh et al. (2013) combine this method with tide gauge observations to produce present day extreme water level probabilities around the entire coastline of Australia. The same method is used extensively to refine catastrophic risk models used by the insurance and reinsurance industries (e.g. Hall and Jewson, 2007; Bonazzi et al., 2014).

Simulated storm tracks based on Typhoon Haiyan have been used by Tablazon et al. (2015) and Lapidez et al. (2015) to derive probabilistic hazard maps for the area in the Philippines. The maps produced show the storm-surge-vulnerable areas in the Philippines, illustrated by the flood depth of up to 4 m in some places and extent of up to 6.5 km from the coastline.

Krien et al. (2015) have combined synthetic storms and used an unstructured hydrodynamic model (ADCIRC) and applied it to storm surge risk for the West Indies. They used 50,000 years worth of synthetic storms passing over Guadeloupe and Martinique to get extreme storm surge return levels around the coast of that island group. Shimokawa et al. (2014) use similar schemes (what they call a 'typhoon bogussing scheme') to synthesise typhoons in Ise and Tokyo Bays in Japan. The creation of synthetic cyclones certainly generates enough storms for credible statistics to be derived but the highly regionalised nature of these studies and the variety of approaches (e.g. Markov Chain, kriging, etc.) suggests that they are not an ideal basis for deriving a consistent global picture of storm surge climate.

Development of a "true" global storm surge climatology is progressing. The NOC is working with Deltares to develop an optimum global tide-surge model with improved ocean topography. This will allow the skew surge analysis technique to be applied to global model results. Muis et al. (2016) have used a previous version of the Deltares global unstructured model to develop a global reanalysis of storm surges and extreme sea levels (the so-called GTSR data set). The GTSR covers the entire world's coastline and consists of a time series of tides and surges, and estimates of extreme sea levels. Validation shows good agreement between modelled and observed sea levels, and that the performance of GTSR is similar to many regional hydrodynamic models. Due to the limited resolution of the meteorological forcing, extremes are slightly underestimated. We anticipate that the tidal improvements brought about in this Task will lead to better agreement and more accurate estimates overall.



## 6. Future work in Task 8.2

The work described in this report sets the direction for the remainder of this Task. In AtlantOS Task 8.2, we will apply the methodology of Williams et al. (2016) to a wider, global set of tide gauge data as described in section 4 above. High quality tide gauge data, where they are available, are the best basis for storm surge climate analysis. This underlines the importance of AtlantOS Task 4.3 (WP4): *"to strengthen access to sea level data networks for the Atlantic region and produce a comprehensive sea level observing site catalogue to document and benchmark information"*. That task will develop a comprehensive South Atlantic sea level observing site catalogue (including sensors, benchmarks, maps and images) [D4.1] and will provide best practice for further improvements in the global catalogue of tide gauge data (as well as identifying regions where investment in sea level measuring infrastructure is most needed).

The work in Task 8.2 will be supported by a wider global contribution as part of the JCOMM ETWCH storm surge climatology project. The observational analyses will be hosted on a permanent website which already exists as a prototype:

<http://noc.ac.uk/science-technology/climate-sea-level/sea-level/skew-surges/storm-surges>

The data will ultimately make a world map of storm surge distributions based on a consistent approach to derivation of storm surge climate from observations, and this will form part of the WP8 web page which is currently under development (the prototype lander page is shown in Figure 4)



Figure 4. Schematic of the WP8 webpage

Each WP8 Task page will follow the basic structure of EMODNET MedSea challenges - see: <http://www.emodnet-mediterranean.eu/portfolio/oil-platforms-leak/>. For Task 8.2, users will be able to drill down and connect to the full storm surge climate records.

Working in partnership with Deltares, work has begun to optimize the global tidal solution in a new version of the unstructured model, based on an improved representation of the ice sheet grounding line in the southern ocean. We intend to run a fully-coupled tide-surge reanalysis to deliver an update to the GTSR data set. Finally, we propose to use the global tide-surge model along with a synthetic tropical cyclone approach to attempt to improve

the statistics of extreme sea levels for the Indian Ocean (this region being relatively understudied) by using a single ocean model for the entire region. The optimized global tide-surge model will lend itself to future studies of the changing climate of storm surges, as climate models begin to operate at a resolution that better resolves the structures of tropical weather systems.

## References

- Karthik Balaguru, David R. Judi, and L. Ruby Leung. Future hurricane storm surge risk for the US gulf and Orida coasts based on projections of thermodynamic potential intensity. *Climatic Change* , 138(1-2):99-110, SEP 2016. ISSN 0165-0009. 10.1007/s10584-016-1728-8.
- Bonazzi, A., A. L. Dobbin, J. K. Turner, P. S. Wilson, C. Mitas, E. Bellone, (2014) A Simulation Approach for Estimating Hurricane Risk over a 5-yr Horizon, *Weather, Climate, and Society*, 6, 1, 77
- Heather Cannaby, Matthew D. Palmer, Tom Howard, Lucy Bricheno, Daley Calvert, Justin Krijnen, Richard Wood, Jonathan Tinker, Chris Bunney, James Harle, Andrew Saulter, Clare O'Neill, Clare Bellingham, and Jason Lowe (2016) Projected sea level rise and changes in extreme storm surge and wave events during the 21st century in the region of singapore. *Ocean Science* , 12 (3):613-632
- Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea Level Change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.
- Conte, D., Lionello, P., 2013. Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. *Global Planet. Change* 111, 159-173.
- de Vries, H., Breton, M., de Mulder, T., Krestenitis, Y., Ozer, J., Proctor, R., Ruddick, K., Salomon, J. C., and Voorrips, A. (1995) A comparison of 2-D storm surge models applied to three shallow European seas, *Environ. Softw.*, 10, 23–42.
- Debernard, J.B., Røed, L.P., 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus A* 60, 427-438.
- R. Gayathri, P. L. N. Murty, Prasad K. Bhaskaran, and T. Srinivasa Kumar (2106) A numerical study of hypothetical storm surge and coastal inundation for Aila cyclone in the Bay of Bengal. *Environmental Fluid Mechanics* , 16(2):429-452
- Gräwe, U., Burchard, H., 2012. Storm surges in the Western Baltic Sea: the present and a possible future. *Clim. Dyn.* 39, 165-183.
- Haigh, Ivan; Macpherson, Leigh; Mason, M.S.; Wijeratne, E.M.S.; Pattiaratchi, Charitha; Crompton, R.P.; George, S. (2014) Estimating present day extreme water level exceedance probabilities around the coastline of Australia: Tropical cyclone-induced storm surges. *Climate Dynamics*, Vol. 42, No. 1-2, 01.01.2014, p. 139-157.
- Haigh, Ivan D.; Wadey, Matthew P.; Wahl, Thomas; Ozsoy, Ozgun; Nicholls , Robert J.; Brown, Jennifer M.; Horsburgh, Kevin; Gouldby, Ben. 2016 [Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK](https://doi.org/10.1038/sdata.2016.107). *Scientific Data*, 3. 160107. [10.1038/sdata.2016.107](https://doi.org/10.1038/sdata.2016.107)
- Hall, T., and S. Jewson, (2007) Statistical modelling of North Atlantic tropical cyclone tracks. *Tellus*, 59A, 486–498.
- Hemer, M.A., Y Fan, N Mori, A Semedo, XL Wang (2013) Projected changes in wave climate from

a multi-model ensemble. *Nature climate change* 3 (5), 471-476

Howard, T., Lowe, J., Horsburgh, K., 2010. Interpreting Century-Scale Changes in Southern North Sea Storm Surge Climate Derived from Coupled Model Simulations. *J. Clim.* 23, 6234-6247.

IPCC. (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, in: C. B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.) (Ed.). pp. 582 pp.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jordà, G., Gomis, D., Álvarez-Fanjul, E., Somot, S., 2012. Atmospheric contribution to Mediterranean and nearby Atlantic sea level variability under different climate change scenarios. *Global Planet. Change* 80–81, 198-214.

Sooyoul Kim, Nobuhito Mori, Hajime Mase, and Tomohiro Yasuda (2015) The role of sea surface drag in a coupled surge and wave model for typhoon Haiyan 2013. *Ocean Modelling* , 96(1):65-84

Y. Krien, B. Dudon, J. Roger, and N. Zahibo (2015) Probabilistic hurricane-induced storm surge hazard assessment in Guadeloupe, Lesser Antilles. *Natural Hazards and Earth System Sciences* , 15(8):1711-1720

J. P. Lapidez, J. Tablazon, L. Dasallas, L. A. Gonzalo, K. M. Cabacaba, M. M. A. Ramos, J. K. Suarez, J. Santiago, A. M. F. Lagmay, and V. Malano (2105) Identification of storm surge vulnerable areas in the Philippines through the simulation of typhoon Haiyan-induced storm surge levels over historical storm tracks. *Natural Hazards and Earth System Sciences* , 15(7):1473-1481

Han Soo Lee and Kyeong Ok Kim (2015) Storm surge and storm waves modeling due to typhoon Haiyan in November 2013 with improved dynamic meteorological conditions. In V Sundar, SA Sannasiraj, K Murali, and V Sriram, editors, 8TH INTERNATIONAL CONFERENCE ON ASIAN AND PACIFIC COASTS (APAC 2015) , volume 116 of *Procedia Engineering* ,34 pages 699-706. IIT Madras; APAC Council

Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S. (2009). UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK. ISBN 978-1-906360-03-0

Marcos, M., Jordà, G., Gomis, D., Pérez, B., (2011) Changes in storm surges in southern Europe from a regional model under climate change scenarios. *Global Planet. Change* 77, 116-128.

Marcos, M., Calafat, F. M., Berihuete, Á. & Dangendorf, S. (2015) Long-term variations in global sea level extremes. *Journal of Geophysical Research: Oceans* 120, 8115–8134.

Kathleen L. McInnes, Kevin J.E. Walsh, Ron K. Hoeke, Julian G. OGrady, Frank Colberg, and Graeme D. Hubbert (2014) Quantifying storm tide risk in Fiji due to climate variability and change. *Global and Planetary Change* , 116:115-129, 2014. ISSN 0921-8181.

Meier, H.E.M., Broman, B., Kjellstrom, E. (2004) Simulated sea level in past and future climates of the Baltic Sea. *Climate Research* 27, 59-75.

Menendez, M. and Woodworth, P.L. (2010) Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *J. Geophys. Res.*, **115**, C10011

Nobuhito Mori, Masaya Kato, Sooyoul Kim, Hajime Mase, Yoko Shibutani, Tetsuya Takemi, Kazuhisa Tsuboki, and Tomohiro Yasuda. Local amplification of storm surge by super typhoon Haiyan in Leyte Gulf (2014) *Geophysical Research Letters* , 41(14):5106-5113

Nobuhito Mori and Tetsuya Takemi (2016) Impact assessment of coastal hazards due to future

changes of tropical cyclones in the North Pacific ocean. *Weather and Climate Extremes*, 11:53-69, 2016. ISSN 2212-0947

Sanne Muis, Martin Verlaan, Hessel C. Winsemius, Jeroen C. J. H. Aerts, and Philip J. Ward (2016) A global reanalysis of storm surges and extreme sea levels. *Nature Communications* , 7:11969, <http://dx.doi.org/10.1038/ncomms11969>

S. Pattanayak, U. C. Mohanty, and A. D. Rao (2016) Simulation of storm surges in the Bay of Bengal using one-way coupling between MNN-WRF and IITD storm surge model. *Marine Geodesy* , 39(5):376-400

Pugh, D. & Woodworth, P. (2014) *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*, Cambridge University Press.

Shinya Shimokawa, Tomokazu Murakami, Satoshi Iizuka, Jun Yoshino, and Takashi Yasuda (2014) A new typhoon bogussing scheme to obtain the possible maximum typhoon and its application for assessment of impacts of the possible maximum storm surges in Ise and Tokyo bays in Japan. *Natural Hazards* , 74(3):2037-2052

Sterl, A., H. van den Brink, H. de Vries, R. Haarsma, and E. van Meijgaard (2009) An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. *Ocean Science*, 5(3), 369-378.

J. Tablazon, C. V. Caro, A. M. F. Lagmay, J. B. L. Briones, L. Dasallas, J. P. Lapidez, J. Santiago, J. K. Suarez, C. Ladiero, L. A. Gonzalo, M. T. F. Mungcal, and V. Malano (2015) Probabilistic storm surge inundation maps for metro Manila based on Philippine public storm warning signals. *Natural Hazards and Earth System Sciences* , 15(3):557-570

Hiroshi Takagi and Wenjie Wu (2016) Maximum wind radius estimated by the 50 kt radius: improvement of storm surge forecasting over the western north Pacific. *Natural Hazards and Earth System Sciences* , 16(3):705-717

Vousdoukas, M.I., Voukouvalas, E., Annunziato, A., Giardino, A., Feyen, L., (2016) Projections of extreme storm surge levels along Europe. *Clim. Dyn.* 47, 3171–3190.

Vickery, P.J., Skerlj, P.F., Twisdale, L.A. (2000) Simulation of hurricane risk in the U.S. using empirical track model. *J Struct Eng* 126(10):1222–1237

Wahl, T. & Chambers, D. P. (2016) Climate controls multidecadal variability in U. S. extreme sea level records. *Journal of Geophysical Research: Oceans* 121, 1274–1290.

Williams, J., K. J. Horsburgh, J. A. Williams, and R. N. F. Proctor (2016), Tide and skew surge independence: New insights for flood risk, *Geophys. Res. Lett.*, 43, 6410–6417, doi:[10.1002/2016GL069522](https://doi.org/10.1002/2016GL069522).

Woodworth P.L., Blackman D.L. (2004) Evidence for systematic changes in extreme high waters since the mid-1970s. *J Clim* 17(6):1190–1197

Dong-mei Xie, Qing-ping Zou, and John W. Cannon (2016) Application of SWAN + ADCIRC to tide-surge and wave simulation in Gulf of Maine during Patriot's Day storm. *Water Science And Engineering* , 9(1):33-41, 2016.

Zhaoqing Yang, Taiping Wang, Ruby Leung, Kathy Hibbard, Tony Janetos, Ian Kraucunas, Jennie Rice, Benjamin Preston, and Tom Wilbanks (2014) A modeling study of coastal inundation induced by storm surge, sea-level rise, and subsidence in the Gulf of Mexico. *Natural Hazards* , 71(3):1771-1794, APR 2014. ISSN 0921-030X. 10.1007/s11069-013-0974-6.

Tomohiro Yasuda, Sota Nakajo, SooYoul Kim, Hajime Mase, Nobuhito Mori, and Kevin Horsburgh (2014) Evaluation of future storm surge risk in east Asia based on state-of-the-art climate change projection. *Coastal Engineering* , 83:65-71, 2014. ISSN 0378-3839.

Heng Zhang and Jinyu Sheng (2015) Examination of extreme sea levels due to storm surges and tides over the Northwest Pacific ocean. *Continental Shelf Research* , 93:81-97, 2015. ISSN 0278-4343.